The Harvest Rate Model for Klamath-River Fall Chinook Salmon: Model Definition, Solution, and Implementation

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Abstract

The fall run of chinook salmon in the Klamath River supports important ocean and river fisheries. The Klamath Harvest Rate Model (KHRM), a fishery population model, is used to project the maximum harvest level that satisfies all constraints of management policy, including allocation among ocean, river tribal, and river-recreational harvesting segments; a minimum spawning escapement goal; and a maximum spawner-reduction rate. The KHRM is a simple, time-aggregated model whose projections provide a starting point for further analysis, with more detailed models, of a season structure for each year's fishery.

Until recently, the KHRM was implemented as a computer spreadsheet, with no documentation other than the spreadsheet itself. Optimal harvest levels were found by trial-and-error entry of values, which were manually changed until the answer was obtained. This was extremely time consuming. Here, we make two major improvements to the KHRM. First, we set forth the mathematical equations underlying the model, and thus provide the first formal documentation of the KRHM, including several corrections and refinements. Second, we derive an analytical solution to the model under present management policy. In the Appendix, we describe a computer program (written in Fortran) that implements the KHRM and solves directly for the optimal level of harvest.

Based on our experience in translating this model from a computer spreadsheet, we briefly discuss several issues surrounding mathematical models in fishery management. Because computer spreadsheet programs obscure the structure of a model (as embodied in its mathematics), procedural languages are better, and more transparent, tools for implementing formal management models. They are also more amenable to quality control. The use of a procedural language makes easier, but does not reduce the need for, the mathematical exposition of a model distinct from its implementation as a computer program. Complementing the mathematics, the objectives and methods of any model used in management should be clearly documented in words.

1 Introduction

The fall run of chinook salmon (*Oncorhyncus tshawytscha*) in the Klamath River supports an important salmon fishery along the northern Pacific coast of the U.S., particularly in California. The fishery is actively managed by the Pacific Fishery Management Council under advice given by the Klamath Fishery Management Council. An overview of the fishery is given by Pierce (1991a, 1991b), and of its management by Pierce (1998).

In the management process, several mathematical models are used to project the effects of proposed management regimes and season structures. A key member of this group of models is the Klamath Harvest Rate Model, or KHRM, which embodies the concept of "harvest rate management" that was developed for this fishery in the 1980's (KRTT, 1986). The KHRM is a simple, time-aggregated model whose projections provide a starting point for further analysis, with more detailed models, of possible season structures for each year's fishery. The KHRM is used to estimate, in three segments of the fishery, the maximum harvests that are consistent with present management policy. The present management rules can be summarized as follows:

1. Take the maximum harvest of adults (ages 3, 4, 5) possible; however,
2. Removals must not reduce the spawning escapement below a predetermined minimum or *spawner floor*; moreover,
3. Removals must not reduce the spawning escapement beyond a maximum allowable proportion (compared to the escapement with no fishing), here termed the maximum *spawner-reduction rate.*
4. In addition, harvests in the three fishery segments (ocean, river tribal, and river recreational) must be in accordance with predetermined harvest-sharing agreements, which at present allocate portions of the catch to the Yurok and Hoopa Tribes, the ocean fishery, and the nontribal river fishery.

Until recently, the KHRM was implemented as a computer spreadsheet. While that implementation was useful in the management process, it had two major drawbacks. First, it was effectively undocumented, except for the spreadsheet itself; and second, it was solved by a time-consuming process of human trial and error.

In this paper, we resolve both shortcomings. First, we document the mathematical equations that form the model itself (independent of implementation). Second, we derive an analytical solution to the KHRM under present management policy. The Appendix describes a computer program in Fortran that embodies that solution.

2 Structure of the KHRM

In this section, the KHRM is defined in words and equations. The symbols used in the paper are summarized in Table 1. Table 1 near here.

Depending on the context, symbols bear no, one, or two subscripts. When two subscripts are used, the first indicates segment of the fishery, and the second indicates age of the fish. When one subscript is used, the corresponding quantity is either age-independent (if a rate) or a sum across ages (if a quantity of fish). When no subscript is used, the corresponding quantity is a sum across all segments and ages. Upper-case letters are generally used for quantities representing numbers of fish; lower-case letters are used for subscripts, proportions, or rates. Throughout the paper, all rates are simple proportions.

2.1 Known and Unknown Quantities

The quantities in Table 1 are of three types: constraints, biological parameters, and unknowns. The *constraints* are the required spawning escapement in natural areas $\check{E}'$, the proportion of the total harvest allocated to the tribes π_t, and the proportion of the non-tribal harvest allocated to the river-recreational segment π_r. The values of these constraints are set by management policy. Two other constraints may also be applied: a maximum spawner-reduction rate $\phi_{\max}$, which limits the harvest rate at large stock sizes, and a minimum spawner-reduction rate $\phi_{\min}$, which allows a small amount of fishing when the spawning-floor criterion cannot be satisfied. Current management policy includes a maximum spawner-reduction rate of 67%. A minimum spawner-reduction rate, sometimes termed a “de minimus” fishery, is not part of current policy, but is under study.

The *biological parameters* in Table 1 are such quantities as the proportion mature at age, proportion of legal size at age, and the dropoff mortality rates in different fishery segments. These quantities are presumed known when using the KHRM. In practice, estimates of them are available.

The *unknowns* in Table 1 are the allowable age-4 ocean contact rate c_o (defined below), the tribal harvest H_t, and the river-recreational harvest H_r. Current management methods dictate this structure, in that the ocean fishery is managed by effort limitation, which more or less directly sets c_o, while the river fisheries (tribal and recreational) are managed by quotas, which directly set H_t and H_r. For any set of river harvest quotas $\{H_t, H_r\}$, there is a corresponding set of river contact rates $\{c_t, c_r\}$, and the development below uses the rates, rather than numerical harvests, for simplicity of presentation.

In the description of the KHRM that follows, it is assumed that the three contact rates are known. This provides a logical presentation and can be used to project the escapement under those contact rates. In §3, the method of solving for the unknowns (the ocean contact rate and the two river quotas), given the constraints and the biological parameters, is explained.

2.2 Ocean Impacts

The KHRM sequentially models the ocean, tribal, and river-recreational segments of the fishery throughout a fishing season, considered to start on May 1. Catch taken in the ocean fishery during the previous fall is not modeled in detail, but is added to the summer ocean catch when evaluating the harvest-sharing agreements. Typically, the fall catch has been converted to *summer-equivalent* catch before being used in the KHRM. The conversion to summer-equivalent catch is made by multiplying the fall ocean harvest by the assumed winter survival rates (0.5, 0.8, and 0.8 for ages 2, 3, and 4, respectively). This conversion is intended to approximate the number of harvested fish that otherwise would have survived until the start of the main summer fishery on May 1.

Computations for the summer ocean fishery start with external estimates of May 1 ocean population sizes at age, N_a. These estimates are derived from a linear regression predicting N_a from the escapement of age $a-1$ fish observed in the previous year. In fitting the regression, estimates from cohort analyses [catch-at-age analyses using methods similar to those of Pope (1972)] of historical cohorts are used for N_a, and estimates made from various observational data are used for the escapement of age $a-1$ fish (J. Barnes, U.S. Fish and Wildlife Service, Eureka, CA, pers. comm.). As throughout the KHRM, ages 3, 4, and 5 are represented.

The first quantity modeled within the KHRM itself is the number of fish $C_{o,a}$ of age a contacted by the summer ocean fishery. By "contacted" we mean fish that are caught and successfully retrieved. The number contacted at age is defined as the product of the preseason ocean abundance at age, the fully-recruited (age 4) ocean contact rate, and the age-specific vulnerability:

$$C_{o,a} = N_a c_o v_{o,a} \tag{1}$$

where $v_{o,4} \equiv 1$. The product $c_o v_{o,a}$ is thus equivalent to an age-specific contact rate.

From the number of fish contacted, the age-specific summer ocean harvest deaths $H_{o,a}$ and shaker (catch-and-release) deaths $S_{o,a}$ are modeled, based on the age-specific proportion ℓ_a of fish of legal size:

$$H_{o,a} = C_{o,a}\, \ell_a \tag{2}$$

$$S_{o,a} = C_{o,a}(1 - \ell_a)\, s_a \tag{3}$$

Equations (2) and (3) assume that fishermen accurately observe when a fish is undersized and only then shake it from the hook.

A third type of mortality, *dropoff mortality,* occurs when a fish is hooked, then lost from the hook unintentionally, and it dies as a result of the encounter. Following the practice of the Pacific Fishery Management Council, the KHRM calculates dropoff mortality as a specified multiple d, $d \ll 1.0$, of the number of fish contacted (STT, 1994). Thus, dropoff deaths in the summer ocean fishery are modeled as

$$D_{o,a} = C_{o,a}\, d_{o,a} \tag{4}$$

Total summer ocean impacts at age are defined as the sum of ocean harvest, shaker, and dropoff deaths:

$$I_{o,a} = H_{o,a} + S_{o,a} + D_{o,a} \tag{5}$$

The total summer ocean harvest is obtained by summing across ages:

$$H_o = \sum_{a=3}^{5} H_{o,a} \tag{6}$$

with similar expressions being used for the other summer ocean totals: S_o, D_o, and I_o.

At this point, catches from the previous fall (typically in summer-equivalent units) are added, for later use in computing allocations that satisfy the harvest-sharing agreements:

$$H_{\omega,a} = H_{o,a} + H_{f,a} \tag{7a}$$

$$I_{\omega,a} = I_{o,a} + H_{f,a} \tag{7b}$$

In equation (7b), $H_{f,a}$ is used in place of $I_{f,a}$ because the latter is not known. It is anticipated that the resulting bias will be very small, because $H_f \ll H_o$.

2.3 River Impacts

Following the ocean fishery, the number of fish at age remaining in the ocean is considered to be $N_a - I_{o,a}$. The resulting age-specific river run of spawners is that number times the proportion mature:

$$N'_a = (N_a - I_{o,a})m_a \tag{8}$$

In the KHRM, the two river segments, tribal (t) and recreational (r), are treated as independent, rather than competing, sources of mortality. The number of fish at age contacted by the respective fisheries is the product of the number of fish in the river, the corresponding contact rate, and the river vulnerability rate:

$$C_{i,a} = N'_a c_i v_{\rho,a} \ , \qquad i \in \{t, r\} \tag{9}$$

where $v_{\rho,4} \equiv 1$. (The same river vulnerability vector v_ρ is used in both the tribal and river-recreational fisheries.) The number of deaths at age attributable to dropoff is

$$D_{i,a} = C_{i,a} d_i \ , \qquad i \in \{t, r\} \tag{10}$$

and the remaining fraction of contacted fish are assumed harvested:

$$H_{i,a} = C_{i,a}(1 - d_i) \ , \qquad i \in \{t, r\} \tag{11}$$

Because size limits are not used in river fisheries, shaker mortalities do not occur. Tribal impacts at age are defined as the sum of harvest and dropoff deaths:

$$I_{i,a} = H_{i,a} + D_{i,a} \ , \qquad i \in \{t, r\} \tag{12}$$

As with the ocean fishery, the model considers total harvests, dropoff deaths, and impacts to be simple sums:

$$H_i = \sum_{a=3}^{5} H_{i,a} \ , \qquad i \in \{t, r\}$$

with similar expressions applying to D_i and I_i.

2.4 Spawning Escapement

Spawning escapement is computed as the river run less the impacts of the river fisheries:

$$E = \sum_{a=3}^{5} N'_a - I_\rho \tag{13}$$

where the impacts of the river fisheries are given by

$$I_\rho = H_t + D_t \ + \ H_r + D_r \tag{14}$$

Because age-specific information is not available, an age-averaged estimate of the proportion g of spawners in natural areas is used to model the total spawning escapement to natural areas:

$$E' = gE \tag{15}$$

2.5 Summary of the Model

Equations (1) through (15) define how, from a proposed set of contact rates, the KHRM projects the resulting escapement in natural areas, thus indicating whether that set of contact rates allows the escapement goal to be met. By evaluating the KHRM with all contact rates set to zero, the projected spawner-reduction rate ϕ can be computed:

$$\phi = 1 - E'/E'_0$$

where E'_0 is the projected escapement in natural areas under no fishing. Comparing ϕ to ϕ_{min} and ϕ_{max} will indicate whether these constraints on the spawner-reduction rate are met. Finally, the projected harvest ratios π_t and π_r, computed from the projections of H_ω, H_t, and H_r, indicate whether the harvest-sharing agreements are met. Thus, the KHRM framework allows one to evaluate whether a set of contact rates meets the three sets of management constraints.

Our description of the KHRM so far reflects closely the model structure implicit in the original spreadsheet. We have made several corrections, including incorporating the dropoff rate in the ocean fishery and correcting inconsistencies in the treatment of the fall harvest, and clarified the terminology throughout. However, the treatment so far provides no way, other than trial and error, to find those contact rates yielding the largest harvest that satisfies the management constraints. To find those optimum rates, a solution algorithm must be coupled with the KHRM model structure.

3 Solving the Model

The model structure embodied in equations (1) through (15) was deduced by the authors from the original spreadsheet. Given that structure, can the maximum allowable harvest rates be found directly? As suggested above, the answer is yes. For the harvest-sharing agreements to be met, a specific ocean contact rate is consistent with one (and only one) tribal harvest and one (and only one) river-recreational harvest. Thus, given an ocean contact rate, the corresponding ocean, tribal and river-recreational impacts can all be computed. With the impacts known, it is straightforward, from equations (13) and following, to project the ensuing spawning in natural areas and the corresponding spawner-reduction rate. If the spawner-reduction rate is not within the desired bounds, the target escapement in natural areas $\breve{E}'$ can be changed to make it so. Thus the problem has been reduced to finding the ocean contact rate that corresponds to a specified spawning escapement in natural areas. We now explain how this is done.

3.1 Formulating the Solution

From equations (8), (13), and (15), escapement to natural areas E' can be expressed in terms of May 1 ocean abundance, maturity at age, and fishery segment impacts as

$$E' = g\left[\sum_{a=3}^{5}(N_a - I_{o,a})m_a - I_\rho\right] \tag{16}$$

For fixed $\{N_a\}$, $\{m_a\}$, and g, the KHRM implies that E' is a linear function of the ocean contact rate c_o. We demonstrate this by showing that both the ocean impacts I_o and the total river impacts I_ρ are linearly related to the number of ocean contacts C_o, which is proportional to c_o by equation (1).

From §2.2, the ocean impacts are the sum of harvested fish, shaker mortalities, and dropoff mortalities:

$$I_{o,a} = C_{o,a}\left[\ell_a + (1-\ell_a)s_a + d_{o,a}\right] \tag{17}$$

From §2.3, the river impacts can be expressed in terms of the river harvests and dropoff rates as

$$I_\rho = \frac{H_t}{1-d_t} + \frac{H_r}{1-d_r} \tag{18}$$

But as defined by the harvest-sharing agreements, the river harvests H_t and H_r are determined by the ocean harvest H_ω, and thereby by the ocean contacts $C_{o,a}$. Let H represent the total harvest over all segments and time periods: $H \equiv H_\omega + H_t + H_r$. As defined in Table 1, the sharing agreements provide that

$$H_t = H\pi_t \tag{19a}$$

$$H_r = H(1-\pi_t)\pi_r \tag{19b}$$

and

$$H_\omega = H(1-\pi_t)(1-\pi_r) \tag{19c}$$

On solving (19c) for H and substituting the result into (19a) and (19b), we find that equation (18) reduces to

$$I_\rho = \kappa H_\omega = \kappa \sum_{a=3}^{5} \left(C_{o,a}\ell_a + H_{f,a} \right) \tag{20}$$

H_ω being given by equations (7a) and (2), and

$$\kappa = \frac{\pi_t}{(1-\pi_t)(1-\pi_r)(1-d_t)} + \frac{\pi_r}{(1-\pi_r)(1-d_r)} \tag{21}$$

Finally, substituting (17) and (20) into (16) and applying equation (1) shows that, under the sharing agreements, projected escapement to natural areas is a linear function of the age-4 ocean contact rate:

$$E' = \alpha - \beta c_o \tag{22a}$$

where

$$\alpha = g \sum_{a=3}^{5} \left(N_a m_a - \kappa H_{f,a} \right) \tag{22b}$$

and

$$\beta = g \sum_{a=3}^{5} N_a v_{o,a} \Big[(\ell_a + (1 - \ell_a) s_a + d_{o,a}) m_a + \kappa \ell_a \Big] \tag{22c}$$

Thus, given a specific goal $\breve{E}'$ for escapement in natural areas E', the KHRM projects that the age-4 ocean contact rate $\breve{c}_o$ that will exactly meet that goal is

$$\breve{c}_o = \frac{\alpha - \breve{E}'}{\beta} \tag{23}$$

Here, α and β are known quantities in that they depend entirely on the constraints and biological parameters considered known in the model, which means that the trial-and-error approach used formerly is unnecessary. Given π_t, π_r, the biological parameters, and an escapement goal, one can directly compute the appropriate contact rates and the resulting harvests and impacts.

The preceding development assumes that the proportion spawning in natural areas g is constant across ages, an assumption used in the KHRM because age-specific estimates of g are not available. However, this is not a necessary restriction. The computer program QHRM (for "Quick Harvest Rate Model"), described in the Appendix, can accept age-specific values of g and perform the corresponding computations correctly.

4 Discussion

Availability of ready, direct, solutions to the KHRM under a different management scenarios has had several benefits. The most obvious is that a tedious trial-and-error process has been eliminated from an already demanding management procedure, usually conducted under severe time constraints. A further benefit is increased ability to use last-minute data corrections that can become available during the management procedure. A number of resource users have used the improved KHRM, as implemented in the QHRM computer program, to explore the behavior of the model, and this has increased confidence in the model. Finally, the availability of a direct solution makes possible computerized Monte Carlo studies of the likely short- and long-term effects of different management strategies. Such studies are now underway.

Also used in the management process for this stock is the Klamath Ocean Harvest Model (KOHM), essentially a time-and-space disaggregated version of the same model. The KOHM, though more informative on details of the fishing season, lacks a solution algorithm. In present management procedure, KHRM results are used as a starting point for a more detailed analysis, via the KOHM, of possible fishing seasons. Because the two models, KHRM and KOHM, represent the same management and fishing processes, we have attempted in this revision of the KHRM to use the same terminology and notation that are being used in the ongoing revision of the KOHM.

Although the authors have made numerous refinements and corrections to the KHRM, further improvements could be made, as with any management model. For example, the ocean fishery, presented here as a single component, is composed of a commercial troll fishery and a recreational hook-and-line fishery. (The latter takes about 15% of the summer ocean catch.) This distinction has never been elaborated in any version of the KHRM, as the resulting errors are small and are accounted for in the succeeding KOHM analyses.

As in all models of Pacific salmon harvest, the KHRM uses an *ad hoc* mathematical expression to compute dropoff mortality D (fish that are hooked, not retrieved, but die from the encounter). Rather than being a portion of the total fraction of fish hooked, D is computed as an additional multiple of the fish harvested. To do otherwise would require estimating the total fraction of fish hooked but not retrieved, and it is not clear how such a quantity could be estimated. Lawson and Sampson (1996), in a review of gear-related mortalities in salmon fisheries, pointed out that noncatch mortalities are “neither directly observable nor measurable” and considered estimation of dropoff mortality rates “not feasible.” Nonetheless, any progress in estimating dropoff mortality along the Pacific coast could readily be incorporated into the KHRM.

The solution algorithm outlined here is in two parts. In the first part, the three unknowns are reduced to one; in the second, the solution for that one unknown is found. Because the equations of the model are all linear, it is possible to easily find an analytical solution to the second part. However, with a different population model, that might not alway be the case. If not, it still would be possible to solve for the one unknown by numerical means; e.g. by bisection (Gill et al., 1981). Thus, the ability to find a systematically computable solution does not depend on the linearity of the model.

Having to decipher the underlying mathematical structure of the KHRM from a spreadsheet raised several questions about the role of spreadsheets in fishery management. Computer spreadsheets are powerful tools that have provided the public the ability to construct computer models without formal programming. Because of their conceptual simplicity and their display of intermediate results, spreadsheets are often considered self-documenting. However, spreadsheet formulas refer to cell locations rather than variable names; this can make it difficult to recognize the model's underlying structure, and can require extensive cell-to-cell tracing and manual transcription of formulas in order to fully understand the mathematical basis of the model. If the model becomes more complex over time, as models commonly do, it can become exceedingly difficult to reconstruct the underlying mathematical model from its implementation as a spreadsheet. Thus, the relationship of a result to the input quantities from which it is derived can be quite opaque. This is hardly what one would think of as self-documenting.

We believe that the analytical structure of a model and its implementation in the form of a computer program are two distinct entities that should be separately described and maintained. Examining the analytical expressions (equations) comprising a model can lead to important insights (e.g., our observation that the model solution could be expressed in terms of a single unknown) and full recognition of the model's assumptions and limitations. A computer program, spreadsheet or otherwise, is no substitute for an analytic description and analysis of the underlying mathematical model.

We also believe that procedural programming languages are better tools than spreadsheet programs for implementing formal fishery management models. Procedural languages (such as Fortran, Basic, C, or Pascal) are essentially direct translations of mathematical formulas. As a result, it is much easier to verify in a procedural program that computations are being carried out correctly. Also, chance programming errors, though difficult enough to find in a procedural program, are much more difficult to detect in a spreadsheet, because (for example) a computation can be carried out 1,000 times in a procedural program with one line of code, but will usually require 1,000 repetitions of a formula in the spreadsheet. Checking each of those 1,000 entries is a daunting task. In a spreadsheet, an inadvertent slip of a key can modify a cell's formula, and if the modification produces a reasonable result, it will be almost impossible to detect (we discovered several apparent examples of this in the original KHRM spreadsheet). Finally, it is exceedingly difficult to detect and understand modifications made between revisions of a model implemented as a spreadsheet, as formula modifications are not immediately visible. In contrast, tools are available on most computer platforms for detecting and displaying differences between text files, such as those containing source code of procedural programs. Implementing a fisheries management model such as the KHRM in a procedural language is therefore advantageous in that the model's underlying structural formulas and relationships are more transparent and, as a result, easier to verify, maintain, and decipher.

Do we advocate the abolition of spreadsheets? Certainly not, for informal or experimental analyses. However, because it is so difficult to assure their correctness, we recommend that their use be avoided, when possible, for formal or repeated analyses, such as those used by Fishery Management Councils in the performance of their duties.

We strongly advocate that models used in formal fishery management contexts should be formally documented. This worthwhile goal may not always be achievable in practice, but it can build public trust, allow for repetition of analyses in succeeding years, and stimulate progress in development of better models.

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Table 1. List of variables used in the Klamath Harvest Rate Model.

Variable	Description
a	subscript denoting age, $a \in \{3, 4, 5\}$
i	subscript denoting segment of fishery, $i \in \{f, o, \omega, t, r, \rho\}$
f	ocean segment, previous fall
o	ocean segment, summer
ω	both ocean segments
t	river segment, tribal
r	river segment, recreational
ρ	both river segments
c	fully-recruited (age 4) contact rate, proportion
C	number of fish contacted (hooked) by fishery
d	dropoff mortality rate (as proportion)
D	dropoff deaths, number of fish
E	spawning escapement, number of fish
E'	projected spawning escapement in natural areas, number of fish
$\check{E}'$	target spawning escapement in natural areas, number of fish
ϕ	spawner reduction rate (proportion reduction in number of spawners, relative to number with no fishing)
g	proportion of spawning that occurs in natural areas
H	number of fish harvested (landed) by fishery
I	impact (number of fish killed by fishery)
ℓ	proportion of fish of legal size
m	proportion mature
N	number of fish in ocean prior to ocean fishery (May 1)
N'	number of fish in river prior to river fisheries (“river run” or “ocean escapement”)
π_t	proportion of *total* harvest taken by tribal fisheries
π_r	proportion of *non-tribal* harvest taken by river-recreational fishery
s	shaker (catch-and-release) mortality rate, proportion
S	shaker deaths, number of fish
v	vulnerability to gear at age a

Appendix: The QHRM Computer Program

The Quick Harvest Rate Model, or QHRM, is a computer program that combines the model structure of the KHRM with the algorithm described above to find the optimum values of $c_{o,a}$, H_t, and H_r. The authors have implemented the QHRM in standard ISO Fortran 90, so that it should be portable to any modern Fortran compiler; we will provide machine-readable copies of the source code and executable files upon request. The computational flow of the QHRM program is given (in abbreviated form) in Figure A-1. Figure A-1 near here.

Use of the QHRM is simple, if old-fashioned. The program has a file-based user interface. The required biological parameters and starting values of N_a are read from an input file, supplied by the user and always named QHRM.INP. A sample input file is given in Appendix A.1. To protect the user's data, the input file should be made with another name and copied to QHRM.INP before running the QHRM. The program is then started by typing QHRM.

The program's output is similarly old-fashioned. A few screen messages indicate that the program is running, and all results are written to the file QHRM.OUT. A sample output file corresponding to the sample input file is given in Appendix A.2. To prevent the output's being overwritten, the output file should be renamed before the QHRM is run again.

For ease of editing and printing, the input and output files are plain ASCII. The sole exception is that if the number '1' rather than '0' is entered on line 2 of the input file, the output will be preceded by printer control codes that will allow the output, which is 120 columns wide, to be printed on a single page by many current laser printers.

A.1 Listing of QHRM.INP (sample input file)

```
'Klamath QHRM - Sample Input File'    ## Title, <= 70 chars.
0                             ## Integer: 1 for LaserJet, 0 for ASCII output
3.5d4                         ## Minimum escapement (nfish) in nat areas
0.0d0  0.667d0                ## Minimum and maximum spawner-redn rates
0.50d0                        ## Desired tribal share (proportion of total)
0.12d0                        ## Desired river rec share (proportion of non-tribal)
0.88d0   1d0  1d0             ## Ocean vulnerability at age
0.8d0    1d0  1d0             ## Proportion legal at age in ocean
0.25d0   0d0  0d0             ## Shaker mortality rate at age
0.337d0  0.936d0  1.0d0       ## Proportion mature at age
1.345d5  3.76d4   1.6d3       ## Starting stock size at age
0d0      175d0      5d0       ## Previous fall harvest at age
0.59d0   1d0      1d0         ## River vulnerability at age
6.2d-1   6.2d-1  6.2d-1       ## Proportion spawning in natural areas at age
0.05d0   0.08d0  0.02d0       ## Dropoff rates - ocean, tribal, nontribal
```

A.2 Listing of QHRM.OUT (sample output file)

```
QHRM: KLAMATH QUICK HARVEST RATE MODEL (ver 2.03) by M.H. Prager and M.S. Mohr, NMFS Tiburon; after work by USFWS Arcata


Klamath QHRM - Sample Input File                                                                  16 Jul 1998 at 09:08:00


CONSTANTS AND CONSTRAINTS (Input by User)
========================================================================================================================
        Ocean      River       Prop               Shaker      Ocean     Tribal    Riv-rec       Prop       Prev         May
     vulnerab   vulnerab      legal       Prop    mortal    dropoff    dropoff    dropoff    natural       fall       stock
Age      rate       rate       size     mature      rate       rate       rate       rate   spawners    harvest        size
------------------------------------------------------------------------------------------------------------------------
  3     0.880      0.590      0.800      0.337     0.250      0.050      0.080      0.020      0.620         0.     134500.
  4     1.000      1.000      1.000      0.936     0.000      0.050      0.080      0.020      0.620       175.      37600.
  5     1.000      1.000      1.000      1.000     0.000      0.050      0.080      0.020      0.620         5.       1600.
Sum       .          .          .          .         .          .          .          .          .        180.     173700.
------------------------------------------------------------------------------------------------------------------------
    Minimum escapement in natural areas:                                       35000.
    Minimum, maximum spawner-reduction rate:                          0.000    0.667
    Required tribal proportion of total harvest:                               0.500
    Required river-recreational proportion of non-tribal harvest:              0.120
------------------------------------------------------------------------------------------------------------------------


OCEAN PROJECTIONS
========================================================================================================================
       Summer     Summer     Summer     Summer     Summer      Total      Total      Post-
      contact      ocean     shaker    dropoff      ocean      ocean      ocean     season       River
Age      rate    harvest     deaths     deaths    impacts    harvest   impacts*      stock         run
------------------------------------------------------------------------------------------------------------------------
  3     0.098      9326.       583.       583.     10491.      9326.     10491.    124009.      41791.
  4     0.098      3703.         0.       185.      3888.      3878.      4063.     33712.      31554.
  5     0.098       158.         0.         8.       165.       163.       170.      1435.       1435.
Sum       .       13186.       583.       776.     14545.     13366.     14725.    159155.      74780.
------------------------------------------------------------------------------------------------------------------------
                                                                                 * Assumes fall impacts = fall harvest

RIVER PROJECTIONS (Recreational, Tribal, Total)
========================================================================================================================
       Tribal    Recreat      Total                River-      Total                River-       Total
      dropoff    dropoff    dropoff     Tribal    recreat      river     Tribal    recreat       river
Age    deaths     deaths     deaths    harvest    harvest    harvest    impacts    impacts     impacts
------------------------------------------------------------------------------------------------------------------------
  3      565.        16.       581.      6497.       780.      7276.      7062.       796.       7857.
  4      723.        20.       743.      8314.       998.      9312.      9037.      1018.      10055.
  5       33.         1.        34.       378.        45.       423.       411.        46.        457.
Sum     1321.        37.      1358.     15189.      1823.     17012.     16510.      1860.      18370.
------------------------------------------------------------------------------------------------------------------------


PROJECTED IMPACT RATES (Relative to May 1 Population)
========================================================================================================================
        Ocean      River      River      River       Non-        All
Age    total*     Tribal    recreat      total    Tribal*  segments*
------------------------------------------------------------------------------------------------------------------------
  3     0.078      0.053      0.006      0.058      0.084      0.136
  4     0.108      0.240      0.027      0.267      0.135      0.375
  5     0.107      0.257      0.029      0.286      0.135      0.392
Pop     0.085      0.095      0.011      0.106      0.095      0.191
------------------------------------------------------------------------------------------------------------------------
                                                          * Includes fall harvest, taken before May 1 population estimate

HARVEST AND ESCAPEMENT PROJECTIONS
========================================================================================================================
Harvest regime:                            Type 2  ...... To meet minimum escapement in natural areas
Total harvest:                              30378.
Ocean harvest:                              13366.
River harvest:                              17012.
Tribal harvest:                             15189. ...... which is 50.0% of total harvest.
Non-tribal harvest:                         15189.
River-recreational harvest:                  1823. ...... which is 12.0% of non-tribal harvest.
------------------------------------------------------------------------------------------------------------------------
Total spawning escapement:                  56410.        |
Spawning escapement in nat areas:           34974.        |        Spawner survival rate (rel to no fishing):     0.689
Same, with no fishing:                      50761.        |        Spawner reduction rate (rel to no fishing):    0.311
------------------------------------------------------------------------------------------------------------------------

- All results are subject to roundoff error.  Totals may differ slightly.
```

A.3 Fortran Source for QHRM.F90 (Main Program)

```
!=====================================================================
      PROGRAM QHRM              ! Fortran 90 version, file: QHRM.F90
!
!     Klamath quick harvest rate model     Fortran    M. Prager/M. Mohr
!     (For revision history see bottom of file)
!
!     This version finds the ocean harvest rate that will meet
!     management goals, including tribal and river-recreational
!     fisheries that must be a fixed proportion of the total harvest.
!
!     Management is specified by a maximum spawner-reduction rate and a
!     spawner floor.  A minimum spawning-reduction rate may also be
!     applied, even if the spawning population is below the floor,
!     to yield a "de minimus" fishery.
!
!     This program is based on a spreadsheet by USFWS, Arcata.
!     It was translated into Fortran and features were added by
!
!        Michael H. Prager, SW Fisheries Science Center,
!        National Marine Fisheries Service, Tiburon, California
!        FAX: (415) 435-3675    Internet: Mike.Prager@noaa.gov
!   and
!        Michael S. Mohr (at the same address)
!        FAX: (415) 435-3675    Internet: Michael.Mohr@noaa.gov
! --------------------------------------------------------------------
      use qhrmvar
      implicit none
      real, parameter  :: version = 2.04
      double precision :: Fo,FoCALC,SRR
!
!     Some Key Variables:
!
!     Fo = Ocean "harvest rate" sensu LHRM
!     FoCalc = Function to compute Fo given desired nat escapement
!     SRR = Spawner Reduction Rate for a given fishing regime
!     escgoal = minimum escapement consistent w/ other constraints
!
      write (*,400)
!     ...Read input file
      call readdata
!
!     ...Find "natural" escapement absent fishing (escnat0)
!
      Fo = 0d0                  ! Turn off all fishing
      call evaluate(Fo)         ! Simulate population with Fo = 0
      escnat0 = escnattot       ! "Natural" escapement absent fishing
!
!     Check for case when there is no fishing:
      if (dmrate .eq. 0d0 .and. escnat0 .lt. escgoal_usr) then
         Ftype = 0
         fishery$ = 'Closure (except for fall take)'
      else
!        Under the assumption that we can take all fish over the floor,
!        find the provisional spawner-reduction rate:
```

```
         SRR = 1d0 - (escgoal_usr / escnat0)
!        Is SRR is over the maximum allowed?
         if (SRR .gt. maxrate) then
!           If so, set the escapement goal by the maximum rate:
            escgoal = escnat0 * (1d0 - maxrate)
            ftype = 3
            fishery$ = 'To meet maximum spawner-reduction rate'
!        Is SRR is less than the de minimus rate?
         elseif (SRR .lt. dmrate) then
!           If so, set the escapement goal by the de minimus rate:
            escgoal = escnat0 * (1d0 - dmrate)
            ftype = 1
            fishery$ = 'To meet minimum spawner-reduction rate'
!        If we are colliding with neither min nor max rate, set the
!        escapement goal to the input value (floor):
         else
            escgoal = escgoal_usr
            ftype = 2
            fishery$ = 'To meet minimum escapement in natural areas'
         endif
      endif
!
101   continue
!
!     ... Write message to screen:
      write (*,410) ftype,fishery$

!     ...Compute the ocean harvest rate Fo corresponding to the
!        escapement goal:
      if (ftype .gt. 0) then
         Fo = FoCALC()
         SRR = 1d0 - (escnattot / escnat0)
      endif
!
!     ...Simulate the fishery with the computed harvest rate:
      call evaluate(Fo)
!
!     ...Write the results to a file:
      call wrtout(version)
      write (*,420)
!
400   format(1x,'*** QHRM running...')
410   format(1x,'*** Type',i2,' fishery: ',a45)
420   format(1x,'*** QHRM done.')
!
      end program qhrm
! ====================================================================
!
      DOUBLE PRECISION FUNCTION FoCALC()
!
!     Find the ocean contact rate (Fo) that will meet the desired
!     escapement target in natural areas.
!
      use qhrmvar
      implicit none
      double precision alpha,beta,k
```

```
      integer i
!
!     ...Sharing agreements (K coefficient)
!
      k = ptribe / ((1d0-ptribe)*(1d0-prr)*(1d0-dtr))
      k = k + ( prr / ((1d0-prr)*(1d0-drr)) )
!
!     ...Alpha and beta coefficients:
!
      alpha = 0d0 ; beta  = 0d0
!
      do i = aa,az
         alpha = alpha + pnat(i) * (n0(i)*pmat(i) - hfall(i)*k)
         beta = beta + pnat(i) * (pmat(i)* (plegal(i) + mshak(i) - &
            mshak(i)*plegal(i) + doc) + plegal(i)*k) * &
            (n0(i) - hfall(i))*vo(i)
      end do
!
!     ...Desired ocean contact rate
      FoCALC = (alpha - escgoal) / beta
!
      return
      END function FoCalc
! ====================================================================
      SUBROUTINE EVALUATE(Fo)
!
!     Given an ocean contact rate (Fo), evaluate the impacts of each
!     fishery on the stock.

      use qhrmvar
      implicit none
      double precision Fo,ret,xsum,trate,rrrate
!
!     ...Copy the ocean contact rate to each age:
      ocrate = Fo
!
!     ...Initialize Sum variables
      hrivtot   = 0d0

!     Evaluate summer ocean harvest & impacts at age:
!
      ncon   = n0 * vo * ocrate              ! Contacts @ age
      hsocn  = plegal * ncon                 ! Summer ocean harvest @ age
      hsocntot = sum(hsocn)                  ! Summer ocean landings
      dshak  = ncon * (1d0-plegal) * mshak   ! Shaker deaths @ age
      dshaktot = sum(dshak)                  ! Shaker deaths
      odrop  = ncon * doc                    ! Dropoff deaths @ age
      odroptot = sum(odrop)                  ! Dropoff deaths
      impocn = hsocn + dshak + odrop         ! Ocean impacts @ age
      impocntot = sum(impocn)                ! Ocean impacts, total
      rem    = n0 - impocn                   ! Remaining fish @ age
      remtot = sum(rem)                      ! Remaining fish, total
      rrun   = rem * pmat                    ! River run @ age
      rruntot = sum(rrun)                    ! River run, total
!
!     ...Additional sum quantities:
```

```
      n0tot = sum(n0)                  ! Fish at start of season
      hfalltot = sum(hfall)            ! Fall ocean landings
      hocntot = hsocntot + hfalltot    ! Total ocean landings
!
!     Evaluate the Tribal Fishery:
!
!     ... Compute what the tribal catch should be:
      htribetot = (hocntot * ptribe) / ((prr-1d0)*(ptribe-1d0))
!     ... Compute the corresponding harvest rate:
      ret = 1d0 - dtr             ! ret = retention rate = 1 - dropoff rate
      xsum = dot_product(rrun,vr)
      trate = htribetot / (ret * xsum)
!     ... Break down tribal harvest by age:
       htribe = trate * ret * rrun * vr
!     ... Compute number of dropoffs:
      tdrop = trate * dtr * rrun * vr
      tdroptot = sum(tdrop)
!
!     Evaluate the river-recreational fishery
!
!     ... Compute what the river-rec catch should be:
!     ... PRR is the river-rec catch as a proportion of non-tribal catch
      hrrtot = hocntot * prr / (1d0 - prr)
!     ... Compute the corresponding harvest rate:
      ret = 1d0 - drr                             ! Retention rate
      rrrate = hrrtot / (ret * xsum)
!     ... Break down river rec harvest by age:
      hrr = rrrate * ret * rrun * vr
!     ... Compute number of dropoffs:
      rrdrop = rrrate * drr * rrun * vr
      rrdroptot = sum(rrdrop)
!
!     Total river impacts and escapement:
      impriv = htribe + tdrop + hrr + rrdrop    ! River impact @ age
      imprivtot = sum(impriv)          ! Total river impacts
      escape = rrun - impriv           ! Escapement @ age
      escapetot = sum(escape)          ! Total escapement
      escnat = escape * pnat           ! Esc @ age in natural areas
      escnattot = sum(escnat)          ! Total esc in natural areas
      hriv   = htribe + hrr            ! River harvest @ age
      hrivtot = sum(hriv)              ! Total river harvest
!
      return
      end subroutine evaluate
! ======================================================================
!
      SUBROUTINE WRTOUT(version)
!
!     Write the output to a plain-text (ASCII) file
!
      use qhrmvar
      implicit none
      real                     :: version
      double precision         :: temp,temp2,temp3,temp4
      double precision         :: io,it,ir,irt,int,itot
      integer                  :: i
```

```
      integer, dimension(8)   :: datime
      !
      character(len=3),parameter,dimension(12) :: month = &
         (/'Jan','Feb','Mar','Apr','May','Jun','Jul','Aug','Sep','Oct','Nov','Dec'/)
      character*1, parameter  :: esc = char(27)
      character*32, parameter :: LJCode = esc // "(10U" // esc // &
         "(s0p16.67h8.50v0s0b0T" // esc // "&l8D"
      !
      !
      open (unit=25, file='QHRM.OUT', status='unknown',action='write', &
         err=101)
      goto 120
      !
101   do  !...(This is the open-file error handler)
         write(*,110)
110      format(/' *** QHRM ERROR: Output file "QHRM.OUT" cannot be ', &
            'opened for writing.'/5x,'Please close the file if open in ' &
            'another program.'/' *** QHRM will stop.'/)
         stop
      end do
!
120   continue
!     ...Get date & time (F90 style)
      call date_and_time(values=datime)
!     ...Output heading:
      if (laserjet == 1) write (25,299) ljcode
      write (25,300) version,title,datime(3),month(datime(2)), &
         datime(1),datime(5),datime(6),datime(7)
!
!     ...Input parameters table (Table 1):
      write (25,340)
      do i = aa,az
         write (25,350) i,vo(i),vr(i),plegal(i),pmat(i), &
            mshak(i),doc,dtr,drr,pnat(i),hfall(i),n0(i)
      end do
      write (25,352) hfalltot,n0tot
      write (25,355) escgoal_usr,dmrate,maxrate,ptribe,prr
!
!     ...Ocean projections table (Table 2):
      write (25,360)
      write (25,361)
      do i = aa,az
         temp  = hsocn(i)+hfall(i)      ! Total ocean harvest
         temp2 = impocn(i)+hfall(i)     ! Total ocean impacts
         write (25,370) i,ocrate(i),hsocn(i),dshak(i),odrop(i), &
         impocn(i),temp,temp2,rem(i),rrun(i)
      end do
         temp2 = impocntot+hfalltot     ! Total ocean impacts
      write (25,380) hsocntot,dshaktot,odroptot, &
         impocntot,hocntot,temp2,remtot,rruntot
!
!     ...River projections table (Table 3):
      write (25,390)
      do i = aa,az
         temp = rrdrop(i) + tdrop(i)    ! River dropoffs
         temp2= htribe(i) + tdrop(i)    ! Tribal impacts
```

```
         temp3= hrr(i) + rrdrop(i)     ! River-rec impacts
         write (25,400) i, tdrop(i),rrdrop(i),temp,htribe(i),hrr(i), &
            hriv(i),temp2,temp3,impriv(i)
      end do
      temp = rrdroptot + tdroptot
      temp2= htribetot + tdroptot   ! Tribal impacts
      temp3= hrrtot + rrdroptot     ! River-rec impacts
      write (25,410) tdroptot,rrdroptot,temp,htribetot,hrrtot, &
         hrivtot,temp2,temp3,imprivtot
!
!     ... Impact rates table (Table 4):
      write(25,430)
      do i = aa,az
         io = (impocn(i)+hfall(i))/n0(i)     ! Ocean impact rate
         it = (htribe(i) + tdrop(i))/n0(i)   ! Tribal impact rate
         ir = (hrr(i) + rrdrop(i))/n0(i)     ! River rec impact rate
         irt = it + ir                       ! River impact rate
         int = io + ir                       ! Non-tribal impact rate
         itot = io + it + ir                 ! Total impact rate
         write(25,440) i,io,it,ir,irt,int,itot
      end do
      io = (impocntot+hfalltot)/n0tot     ! Ocean impact rate
      it = (htribetot + tdroptot)/n0tot   ! Tribal impact rate
      ir = (hrrtot + rrdroptot)/n0tot     ! River rec impact rate
      irt = it + ir                       ! River impact rate
      int = io + ir                       ! Non-tribal impact rate
      itot = io + it + ir                 ! Total impact rate
      write(25,450) io,it,ir,irt,int,itot

!     ... Final harvest and escapement table (Table 5/6):
      temp  = htribetot + hrrtot + hocntot      ! Total harvest
      temp2 = (htribetot / temp) * 100d0
      temp3 = hrrtot + hocntot
      temp4 = (hrrtot / temp3) * 100d0
      write (25,520)
      write (25,530) ftype, fishery$
      write (25,535) temp,hocntot,hrivtot,htribetot,temp2,temp3, &
         hrrtot,temp4,escapetot,escnattot,escnattot/escnat0, &
         escnat0, (1d0 - escnattot/escnat0)
!
!     ... Closing note:
      write (25,560)
!
!     *** Formats for all Tables Follow: ***
!
299   format (A32,$)
!
300   format ('QHRM: KLAMATH QUICK HARVEST RATE MODEL (ver ',F4.2,')', &
         ' by M.H. Prager and M.S. Mohr, NMFS ', &
         'Tiburon; after work by USFWS Arcata', &
         ///,a69,t98,i2,1x,a3,' 'i4,' at ',i2.2,':',i2.2,':',i2.2)
!
!     ...Table 1 follows:
340   format (//'CONSTANTS AND CONSTRAINTS (Input by User)',/,120('='), &
         /,t10,'Ocean',t21,'River',t32,'Prop', &
         t50,'Shaker',t61,'Ocean',t70,'Tribal',t79,'Riv-rec',t92, &
```

```
      'Prop',t102,'Prev',t114,'May',/, &
      t7,'vulnerab',t18,'vulnerab',t31,'legal',t42,'Prop',t50, &
      'mortal',t59,'dropoff',t69,'dropoff', &
      t79,'dropoff',t89,'natural',t102,'fall',t112,'stock',/, &
      'Age',t11,'rate',t22,'rate',t32,'size',t40,'mature',t52,'rate', &
      t62,'rate',t72,'rate',t82,'rate',t88,'spawners', &
      t99,'harvest',t113,'size',/,120('-'))
350   format (I3,2(5x,f6.3),7(4x,f6.3),2(2x,f9.0))
352   format ('Sum',2(7x,'.',3x),7(6x,'.',3x),2(2x,f9.0),/,120('-'))
355   format (4x, &
    'Minimum escapement in natural areas:',t78,f9.0,/,4x, &
    'Minimum, maximum spawner-reduction rate:',t66,2(4x,f6.3),/,4x, &
    'Required tribal proportion of total harvest:',t77,f9.3,/4x, &
    'Required river-recreational proportion of non-tribal harvest:', &
    t77,f9.3,/,120('-'))
!
!     ... Table 2 follows:
360   format (//'OCEAN PROJECTIONS',/,120('='))
361   format (t9,'Summer',t21,'Summer',t33,'Summer',t45,'Summer', &
      t57,'Summer',t70,'Total',t82,'Total',t94,'Post-',/, &
      t8,'contact',t22,'ocean',t33,'shaker',t44,'dropoff', &
      t58,'ocean',t70,'ocean',t82,'ocean', &
      t93,'season',t106,'River'/, &
      'Age',t11,'rate',t20,'harvest',t33,'deaths',t45, &
      'deaths',t56,'impacts',t68,'harvest',t80,'impacts*', &
      t94,'stock',t108,'run',/,120('-'))
370   format(i3,2x,f9.3,1x,8(2x,f10.0))
380   format('Sum',7x,'.',4x,8(2x,f10.0),/,120('-')/,t84, &
      '* Assumes fall impacts = fall harvest')
!
!     ... Table 3 follows:
390   format (/,'RIVER PROJECTIONS (Recreational, Tribal, Total)', &
      /,120('='),/, &
      t9,'Tribal',t20,'Recreat',t34,'Total',t57,'River-', &
      t70,'Total',t93,'River-',t106,'Total', &
      /,t8,'dropoff',t20,'dropoff',t32,'dropoff',t45,'Tribal', &
      t56,'recreat',t70,'river',t81,'Tribal',t92,'recreat',t106, &
      'river',/, &
      'Age',t9,'deaths',t21,'deaths',t33,'deaths',t44,'harvest',t56, &
      'harvest',t68,'harvest',t80,'impacts',t92,'impacts',t104, &
      'impacts',/,120('-'))
400   format(i3,9(2x,f10.0))
410   format('Sum',9(2x,f10.0),/,120('-'))
!
!     ... Table 4 follows:
430   format(//'PROJECTED IMPACT RATES (Relative to May 1 Population)', &
      /,120('='),/, &
      t10,'Ocean',t22,'River',t34,'River',t46,'River', &
      t59,'Non-',t72,'All',/, &
      'Age',t10,'total*',t21,'Tribal',t32,'recreat',t46,'total', &
      t57,'Tribal*',t67,'segments*',/,120('-'))
440   format(i3,5x,f6.3,5(6x,f6.3))
450   format('Pop',5x,f6.3,5(6x,f6.3),/,120('-'),/,t58,'* Includes ', &
      'fall harvest, taken before May 1 population estimate' )

!     ...Table 5/6 follows:
```

```
520   format(/'HARVEST AND ESCAPEMENT PROJECTIONS',/,120('='))
530   format('Harvest regime:',t45,'Type',i2,2x,6('.'),1x,a45)
535   format('Total harvest:',t43,f9.0,/,'Ocean harvest:',t43,f9.0,/, &
         'River harvest:',t43,f9.0,/,'Tribal harvest:',t43,f9.0,1x, &
         6('.'),1x,'which is',f5.1,'% of total harvest.',/, &
         'Non-tribal harvest:',t43,f9.0,/, &
         'River-recreational harvest:',t43,f9.0,1x, &
         6('.'),1x,'which is',f5.1,'% of non-tribal harvest.', &
         /,120('-'),/, &
         'Total spawning escapement:',t43,f9.0,t60,'|',/, &
         'Spawning escapement in nat areas:',t43,f9.0,t60,'|',t69, &
         'Spawner survival rate (rel to no fishing):',t114,f7.3,/, &
         'Same, with no fishing:',t43,f9.0,t60,'|',t69, &
         'Spawner reduction rate (rel to no fishing):',t114,f7.3,/, &
         120('-'))
!
!550   format('Note: Escapement goal was increased to reach minimum ',  &
!        'spawner survival rate.')
!     ...Closing note:
560   format(/'- All results are subject to roundoff error.  Totals' &
         ' may differ slightly.',/,'- QHRM is documented in' &
         ' SWFSC Admin. Report T-97-01, free from Librarian,', &
         ' NMFS, 3150 Paradise Dr, Tiburon, CA 94920.')
!
      return
      END SUBROUTINE WRTOUT
! ======================================================================
      SUBROUTINE READDATA
!
      use qhrmvar
      implicit none
      logical exists
!
!     Check that the input file exists:
!
      INQUIRE (FILE='QHRM.INP', EXIST=exists)
      IF (.not. exists) THEN
         write (*,450)
         stop
      endif
450   format (1x,'QHRM ERROR: The input file must be named QHRM.INP.'/,1x, &
         'A file with that name was not found in the current directory.')
!
      open (unit=20,file='QHRM.INP',status='old',action='read')
!
!     Start reading the data
!
      read (20,*) title                    ! Title for output
      read (20,*) laserjet                 ! 1=print to HPLJ; other=ASCII
      read (20,*) escgoal_usr              ! Desired "natural" escapement
      read (20,*) dmrate,maxrate           ! Minimum spawner-reduction rate
                                           ! (de minimus rate) and maximum
                                           ! spawner-reduction rate
      read (20,*) ptribe                   ! Tribal portion of harvest
      read (20,*) prr                      ! Rec portion of non-tribal harvest
      read (20,*) vo                       ! Ocean vulnerability rate
```

```
!     Note: vulnerability is sometimes called "contact rate"
      read (20,*) plegal                  ! Ocean prop legal @ age
      read (20,*) mshak                   ! Ocean shaker rate @ age
      read (20,*) pmat                    ! Proportion mature @ age
      read (20,*) n0                      ! Starting pop size @ age
      read (20,*) hfall                   ! Fall harvest @ age
      read (20,*) vr                      ! River vulnerability @ age
      read (20,*) pnat                    ! Prop that spawn in nat areas @ age
      read (20,*) doc, dtr, drr           ! Dropoff rates - tribal, riv rec
      close (unit=20)
!
      return
      END SUBROUTINE READDATA
! END OF QHRM
! ====================================================================
!  Revision history
!
!  1.0              Initial release
!  1.1   12 Oct 97   Added minimum survival rate to inputs; allow for
!                   four types of fishery.
!  1.5   Dec 97      Added de minimus rate and bonus rate (though latter
!                   is not yet implemented).  Addeded limiting harvest
!                   rate.  Clarified output.
!  1.6   Feb 98      Corrected logic in implementation of de minimus rate.
!  2.0   Mar 98      Added ocean dropoff rate, totally redesigned output.
!  2.01  Mar 98      Finished version of 2.x
!  2.02  Mar 98      Added LaserJet option
!  2.03  Apr 98      Compiled with Lahey compiler: (1) Some use of F90
!                   constructs; (2) added new date/time routines w/
!                   seconds; (3) single executable for all OS's.
!  2.04  Jul 98      Free format and module added.
! ====================================================================
```

A.4 Fortran Source for QHRMVAR.F90 (Module File)

```
!=============================================================================
!  QHRMVAR.F90    Module with variables for QHRM  -- Prager/Mohr -- July, 1998
!
   MODULE QHRMVAR
      character*70 title
      character*55 fishery$
      integer aa,az,Ftype,laserjet
      parameter (aa=3,az=5)
      double precision doc,dtr,drr,escgoal,escgoal_usr,hfalltot,escnat0
      double precision prr,htribe(aa:az),htribetot,maxrate
      double precision hsocntot,remtot,rruntot,imprivtot,hrivtot
      double precision hocntot,ptribe,n0tot,dshaktot
      double precision impocntot,escapetot,escnattot,dmrate
      double precision vo(aa:az),plegal(aa:az),mshak(aa:az)
      double precision pmat(aa:az),n0(aa:az)
      double precision hfall(aa:az),vr(aa:az),pnat(aa:az)
      double precision hsocn(aa:az),ncon(aa:az)
      double precision dshak(aa:az),impocn(aa:az),impriv(aa:az)
      double precision ocrate(aa:az),hriv(aa:az)
      double precision escape(aa:az),escnat(aa:az),rem(aa:az)
      double precision rrun(aa:az)
      double precision odrop(aa:az),odroptot
      double precision tdrop(aa:az),tdroptot,hrr(aa:az),hrrtot
      double precision rrdrop(aa:az),rrdroptot
   END MODULE QHRMVAR
!=============================================================================
```

Appendix Figure Caption

Figure A-1. Computational flow of QHRM computer program. “SRR” means spawner-reduction rate.

(Figure A-1—Prager and Mohr)